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COMBUSTION OF A CARBON PARTICLE MOVING IN A GAS FLOW

Z. S. Leont'yeva

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COMBUSTION OF A CARBON PARTICLE MOVING IN A GAS FLOW

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(Presented by Academician M. V. Kirpichev)

ABSTRACT

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The descending (free fall) motion of a burning spherical carbon particle in an upstream of air is photographed, the kinematics are analyzed and compared with the equivalent motion of an identical nonburning sphere, hence with the analogous problem without surface chemical reaction. The essential difference is a three- to fourfold increase in drag on the burning (reacting with the flowing medium) particle. An analysis is carried out in terms of the mechanics of a variable-mass point (used in the kinematic treatment of a fuel-dissipating rocket). It is found that the resultant velocity of the escaping mass is dependent on the types of fuel constituting the particle, in this case carbon in the form of 1) electrode carbon; 2) charcoal, hence on the chemical reactivity of the material, as well as the composition of the medium. In a nonenriched air medium, the proportions of CO and CO_2 are roughly equal, the former increasing over the latter with temperature.

Author

There is frequent occasion in engineering to deal with processes accompanied by a variation in the mass of a solid or liquid body moving in a liquid or gas medium. These include all processes related to the evaporation of /1801*

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*Numbers in the margin indicate pagination in the original foreign text.

droplets, the dissolving of particles in a liquid, processes involving the heating of solid fuel particles and the concomitant ejection of volatiles, the combustion of droplets, dust particles, or fragments of solid fuels, etc.

All of these phenomena are characterized by a process of material exchange between the moving droplet or dust particle and the medium. It seems reasonable that the motion of such bodies should not and could not be executed in the same fashion as the motion of bodies that do not interact with the medium in which they are moving; the material interaction of the body with the medium is manifested in its motion. This fact is totally ignored, however, in engineering calculations. If the need arises for analyzing the motion of a body or its time of incumbency in a chamber, the calculations are normally performed on the basis of purely hydrodynamical arguments.

The present paper shows, in the example of a burning carbon particle moving in a gas flow, that the chemical processes involved are determined by the motion of the burning object.

The experiments were performed as follows. A spherical carbon particle that had been previously weighed and measured was placed in a vertical quartz electric furnace; the particle was held in the furnace by means of a fine metal filament stretched out along the diameter of the furnace. The furnace was suspended over a glass tube, into which air was fed from below by a compressor. The mass flow of air was measured by means of a diaghragm and water manometer. Once the particle had ignited, the suspending filament was burned out by an electric current and the particle was left to fall into the oncoming airstream. Its trajectory was recorded on film, which moved in a direction perpendicular to the direction of motion of the particle; the motion picture device was connected through a reducer to an electric motor (fig. 1).

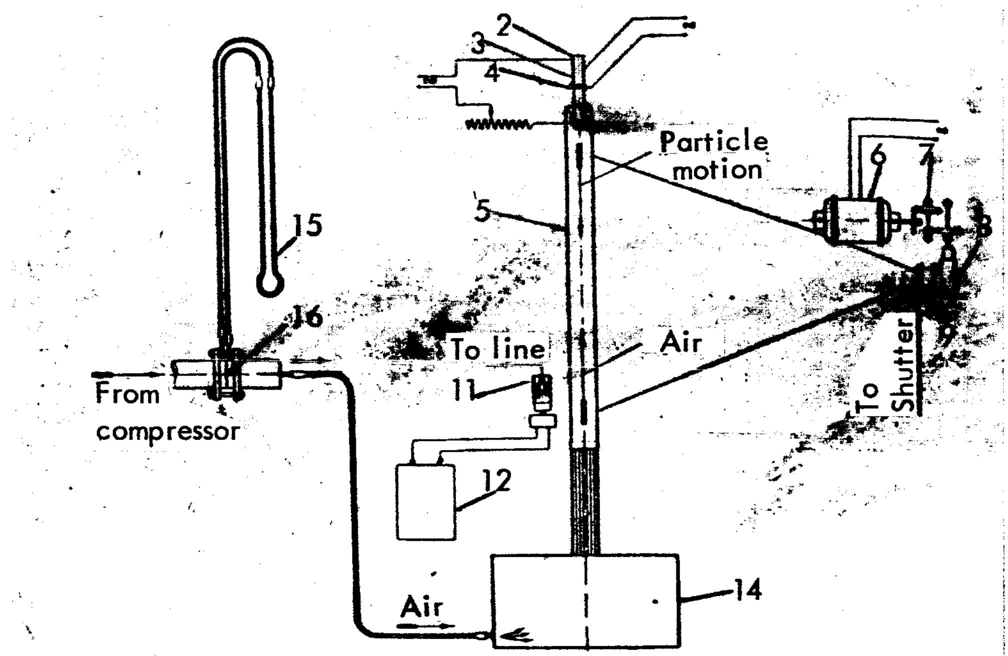

Figure 1. Diagram of Apparatus.

1) Nichrome; 2) Quartz Tube; 3) Metal Filament (d = 0.1-0.15 mm); 4) Carbon Particle; 5) Pyrex Tube; 6) 1.1 kW, 2000 r.p.m., 120 V Motor; 7) Reducer; 8) Camera Attachment; 9) Lamp; 10) Cap with 10 Notches; 11) 60 r.p.m. Warrex Motor; 12) Transformer (rating illegible); 13) Damper; 14) Receiver; 15) Manometer; 16) Diaphragm.

(Translation Note: The key numerals fail to appear in the original figure; the translators have inserted as many as are recognizable from the diagram.)

The velocity and acceleration of the falling particle were determined from the film. The experiments were performed with spherical particles of charcoal (from 3 to 6.5 mm in diameter) and spherical particles of pressed powdered electrode carbon 5 mm in diameter.

The experiment showed that the motion of burning particles occurs with a small and even negative acceleration, i.e., they move much more slowly than is consistent with the laws of hydrodynamics. The effective drag of the burning particle turns out to be three or four times the drag of a hot but noncombusting

sphere of the same type. Figure 2 shows the time dependence of the velocity, calculated for a sphere 5 mm in diameter falling in airless space (1) and in a 1802 resistive medium with a flow velocity of 7 m/sec (2); also shown in figure 2 are the values obtained for the velocity in our experiments (3).

The behavior of these curves is so different that it would be rather difficult to try and explain it in terms of a change in the drag coefficient due to the existence of the temperature difference. Nevertheless, special measurements of the drag coefficient of a heated spherical body were made with air flowing past it and with various temperature differences between the body and the flow. A metal sphere 20 mm in diameter was suspended on a torsion balance (with a sensitivity of 0.005 g per scale division) and was heated with an electrical heating element embedded inside the sphere (fig. 3). The temperature of the inner surface of the metal sphere (wall thickness of 1 mm) in the frontal part was measured by means of a thermocouple. It may be assumed that this corresponded to the surface temperature of the sphere, with only a slight error.

While slowly varying the temperature of the sphere, we determined the drag force on the sphere for three flow regimes, corresponding to the range of variation of the Reynolds number Re in our experiments on particle combustion (800 to 2500). Unfortunately, for temperature differences higher than 500°C we were unable to procure stable values for the drag due to the low power of the heater, but for the low temperature differences obtainable we observed a distinct behavior pattern (fig. 4). The values obtained for the drag coefficient in the case of a cold sphere turned out to be somewhat too high (approximately 1.4 times the tabulated reference values), which is clearly attributable to the influence of the tube walls. As the temperature gradient was increased, the drag increased somewhat, then fell off rapidly. With an increase in the Re number

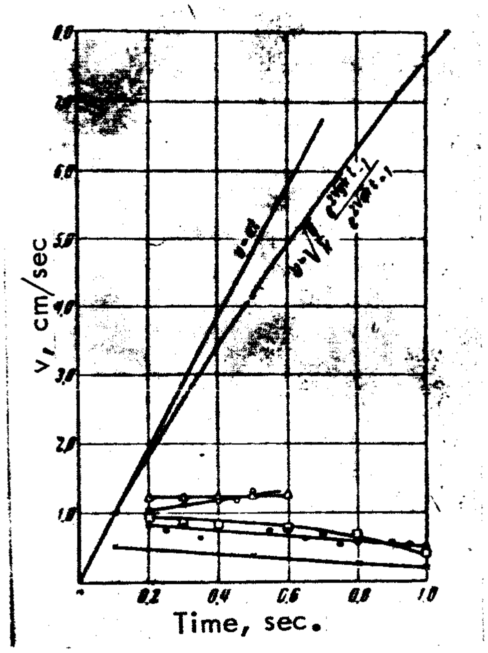

Figure 2. Velocity Curves for Burning Particles.

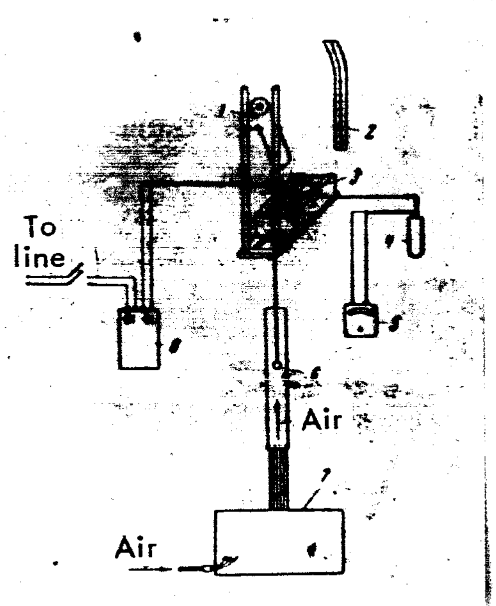

Figure 3. 1) Illuminator; 2) Scale; 3) Mirror; 4) Cold Thermocouple Junctions; 5) Galvanometer; 6) Heated Sphere; 7) Receiver; 8) Transformer.

(i.e., the velocity W) of the free stream, this descent becomes a little more gradual and the reduction in drag is shifted toward higher temperature differences. It is evident that for temperature differences on the order of 800- /1803
1000°C, such as occur is combustion, the drag coefficient should be relatively small and, at any rate, should not increase. These experiments graphically indicate that the large effective drag of the burning particle cannot be attributed to the influence of nonisothermal conditions in the motion of the particle. The increased drag of the burning particle attests to the fact that the combustion process, i.e., the process of material interaction, exerts a pronounced influence on the motion.

The motion of a burning body, reacting with the flow, is not described by the Newtonian equation of motion valid for bodies of constant mass, but by the generalized equation of motion formulated by I. V. Meshcherskiy in 1897 for a

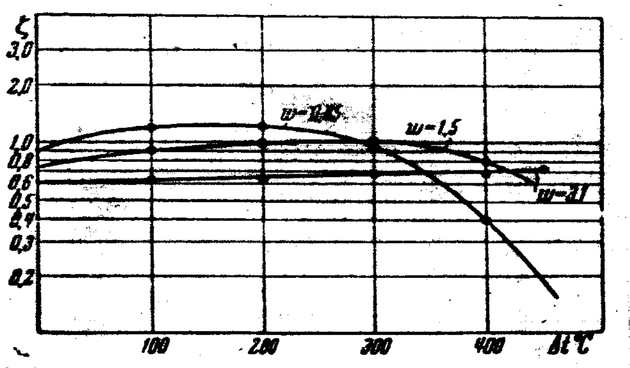

Figure 4

body of variable mass (ref. 1). The motion of a spherical particle whose mass /1804 M varies continuously with time and which is acted upon by forces with a resultant $\vec{F}$ can be described by the Meshcherskiy equation of motion for a variable-mass point:

$$M\frac{d\vec{v}}{dt}=\vec{F}+\frac{dM}{dt}(\vec{u}-\vec{v}), \qquad (1)$$

where $\vec{v}$ is the center-of-mass velocity of the body relative to a fixed coordinate system, dM/dt is the variation in mass of the body per unit time, $\vec{u}$ is the absolute velocity of the departing masses.

Assuming that the combustion products are immediately entrained into the flow past the particle or, in other words, that u = 0, and measuring the velocity and acceleration of the particle experimentally, it is possible to determine the variation in mass and the specific surface rate of combustion from equation (1).

We pursued this objective of determing the rate of combustion by dynamical means, ascertaining the velocity and acceleration experimentally by photographing the descent of a burning spherical carbon particle in an oncoming airstream.

Equation (1) is readily integrated in quadratures. Replacing the value of the mass M by its expression in terms of the radius, we obtain the radius and its time derivative as a function of time, velocity, and acceleration of the particle; this determines the specific surface rate of combustion.

Hence, for a spherical particle of mass $M = \frac{4}{3}\pi r^3 \delta$, where r is the particle radius, δ is its density, and $dM/dt = 4\pi r^2 \delta (dr/dt)$, equation (1) assumes the form

$$\left(g - \frac{dv}{dt}\right)\frac{4}{3}\pi r^3 \delta - \frac{1}{2}\zeta\pi r^2 v^2 + 4\pi r^2 \delta \frac{dr}{dt} = 0,$$

where g is the acceleration of gravity, v is the particle velocity, ζ is the drag coefficient, ρ is the density of the medium in which the particle is moving. We denote the quantity $(g - dv/dt)/v$ by β, the quantity $\frac{1}{2}\zeta\rho/\delta$ by k; then the equation is written

$$\frac{4}{3}\beta r - kv + 4\frac{dr}{dt} = 0. \tag{2}$$

The solution of the homogeneous equation is $r = c \exp(-1/3 \int \beta dt)$. We seek the solution of the inhomogeneous equation (2) by the method of variation of parameters. The final expression for the radius becomes

$$r = \exp\left(-{}^1/_3 \int \beta dt\right)\left[r_0 + \frac{1}{4} k \int v \exp\left({}^1/_3 \int \beta dt\right) dt\right]. \tag{3}$$

The specific surface rate $K_s^c = -\delta\, dr/dt$ then has the form

$$K_s^c = \delta\left[{}^4/_3 \beta \exp\left(-{}^1/_3 \int \beta dt\right)\left(r_0 + \frac{1}{4} k \int v \exp\left({}^1/_3 \int \beta dt\right) dt\right) - kv\right].$$

The quantity K_s^c can then be obtained for any instant of time by approximate integration (graphical method).

However, the values so obtained for the rate of combustion turned out to /1805 be ten times the values of the mean combustion rate obtained by weighing the particles before combustion and again after a definite combustion time, values which agree in order of magnitude with the data of other researchers. For example, in the case of a spherical particle of charcoal 5 mm in diameter and streaming rate of 4 m/sec, the specific surface rate K_s^c determined experimentally is equal to 0.0015 g/cm^2 sec, while the value calculated by the above techniques comes to 0.075 g/cm^{2}sec, taking into account the drag of the particle (with too high a drag coefficient, corresponding to flow past a cold sphere); $K_s^c = 0.042$ with the drag neglected. This contradiction between calculation and experiment indicates, beyond a doubt, the invalidity of the simplifying assumptions on which the calculation was based. This applied above all to the assumption of zero velocity on the part of the separating masses during combustion. An analysis of the solution shows that neglect of the quantity $\vec{u}$ in the term $\frac{dM}{dt}(\vec{u} - \vec{v})$ of equation (1) produces a significant increase in K_s^c as determined from the integral of this equation, if $\vec{u}$ is large. This conclusion regarding the magnitude of the momentum imparted by the departing masses to the particle made it possible to solve another, more interesting problem (interesting in terms of its results); observing the motion of a burning particle and determining the combustion rate by another method under the given experimental conditions, the problem was to calculate the velocity of the departing masses and, on the basis of the postulates of the kinetic theory of matter, to ascertain the relative content of oxides and combustion products escaping from the surface of the burning body.

This problem is of purely theoretical interest and is also important for the analysis of the combustion process, for which it is essential to know the

quantitative ratio of the oxides produced (ref. 2).

If the combustion of a particle in a flow were to proceed uniformly, the momentum imparted by the departing masses to one half of the sphere would be equal in magnitude and opposite in sign to the momentum imparted to the other half, and the total momentum would be equal to zero. The resultant velocity of the departing masses with respect to the sphere would be equal to zero. In a high-velocity stream, however, the combustion of a spherical particle takes place nonuniformly, as is demonstrated by direct sequential photographing of a stationary burning particle (fig. 5a), as well as by the already mentioned facts attesting to the large magnitude of the resultant velocity of the departing masses.

The momentum imparted to the burning hemisphere by particles diffusing away from its surface with a mean velocity $\dot{c}$ turns out to be proportional to the velocity of the departing particles and the mass escaping from this surface.

The local combustion characteristics cannot be measured precisely for a flying particle. We measure experimentally the total change in mass of the particle as a whole and the mean specific surface rate of combustion. By virtue of the free fall and rotation of the particle, the time-average local rate of combustion is near the surface-average rate of combustion. The degree of nonuniformity of combustion is determined by the conditions of flow past the burning particle and the transport of oxygen to its surface. Behind the carbon monoxide flame front, the concentration of oxygen is less than in the frontal portion. Photographs of the burning particles show that the flame front of burning carbon monoxide is situated near the equator in the stern portion of the sphere and its position depends on the conditions of the passing flow.

The exact solution given by A. S. Predvoditelev for the problem of combustion of a spherical carbon particle provides an expression for the concentration distribution of oxygen on the surface of the particle and, hence, the local combustion rates of the spherical particle. /1806

The concentration is

$$C_R = C_0 \exp\left(\frac{16}{19}\frac{\alpha\psi}{Dw_0R^2}\right)\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{\frac{4\alpha}{3R}\sqrt{\frac{\psi}{w_0D}}} \exp(-x^2)\,dx\right].$$

This equation may be approximately represented as an asymptotic series, but again in this case the calculation of the combustion rates proves far too cumbersome. Rough calculations show that, correct to within 10%, it may be approximately assumed that the mass departing from the forward hemisphere is proportional to the total variation in mass and the fraction of the surface from the leading point to the site of detachment of the carbon monoxide flame. This specification of the change in mass is very simple, because the position of the CO flame front is definite. Thus,

$$\frac{dM_1}{dt} = \frac{dM}{dt}\frac{S_1}{S},$$

where dM_1/dt is the variation in mass of the frontal hemisphere per unit time, dM/dt is the variation in mass of the entire particle per unit time, S_1 is the fraction of surface from the leading point to the line of detachment of the CO flame, S is the total surface of the sphere.

The resultant momentum imparted to the burning particle by the masses departing from its surface with a mean velocity c is equal to

$$P = \left(\frac{dM_1}{dt} - \frac{dM_2}{dt}\right)\frac{c}{4} = \frac{dM}{dt}\left(\frac{S_1}{S} - \frac{S-S_1}{S}\right)\frac{c}{4}, \quad P = \frac{dM}{dt}(2x-1)\frac{c}{4}, \qquad (4)$$

where $x = S_1/S$. This equation is valid for angles of detachment greater than 90°. The experiments of O. A. Tsukhanova on the combustion of spherical carbon particles in a flow have shown that the angle of detachment of the CO flame front is always somewhat greater than 90° and depends on the conditions of the passing flow.

The equation of motion of a burning body under the influence of the force of gravity in a flow, where the drag is proportional to the velocity squared, assumes the form

$$M\frac{dv}{dt} = Mg - \zeta F\rho\frac{v^2}{2} + \frac{dM}{dt}\left[(2x-1)\frac{c}{4} - v\right]. \tag{5}$$

Since the velocity of the body v is small in comparison with the quantity c, which is of the same order as the thermal velocities, the quantity v may be neglected. Then, expressing c as in equation (5) and replacing dM/dt in terms of the specific surface rate of combustion K_s^c, we obtain

$$c = \frac{\left(g - \frac{dv}{dt}\right)\delta r - {}^3/_8\,\zeta\rho v^2}{{}^3/_4\,K_s^c(2x-1)}, \tag{6}$$

where δ is the density of the particle, r is its radius, v and dv/dt are its velocity and acceleration, ρ is the density of the flow, ζ is the drag coefficient of the burning particle, x is the ratio S_1/S characterizing the position of the limit of the region of vigorous combustion and detachment of the CO flame. The quantity x is a function of the conditions of flow past the sphere.

The flow near the surface of the burning body behaves differently from /1807 the case of flow past a cold body of the same configuration. The usual laws dictated by hydrodynamics no longer hold. Due to the large temperature gradient and the intense mass transfer between the burning body and gas flow, the boundary layer is turbulent, even though the flow is characterized by a Re number

corresponding to a laminary boundary layer.

The problem of determining the line of detachment of the boundary layer from a burning sphere is of considerable importance with respect to the given problem.

The reduction in drag coefficient when a temperature gradient is present between the surface of the sphere and the flow indicates, from the point of view of the hydrodynamical interpretation of the process, an earlier turbulization of the boundary layer and the onset of a crisis effect. The chemical reaction at the surface is clearly also a powerful source of turbulence in the boundary layer. The combustion of the particle gives rise to an early onset of critical conditions.

If we regard some of the existing photographs, made available to us by O. A. Tsukhanova, of burning spheres (fig. 5b), we wee that the angle of detachment of the layer of burning CO considerably exceeds the angle corresponding to a laminar boundary layer (83°).

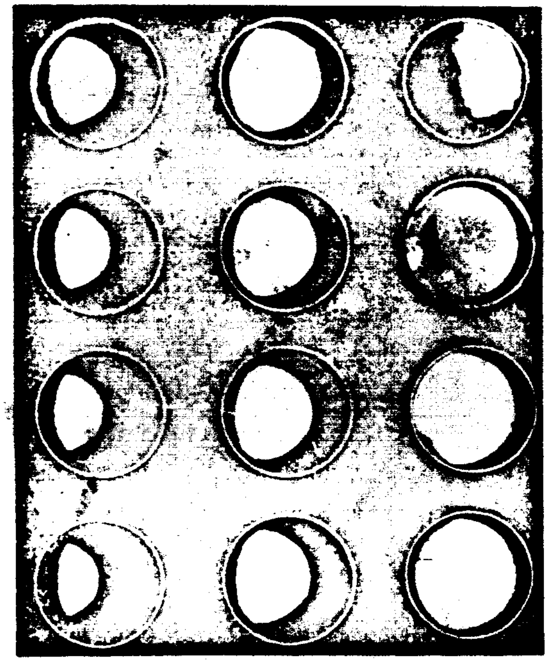

Figure 5a

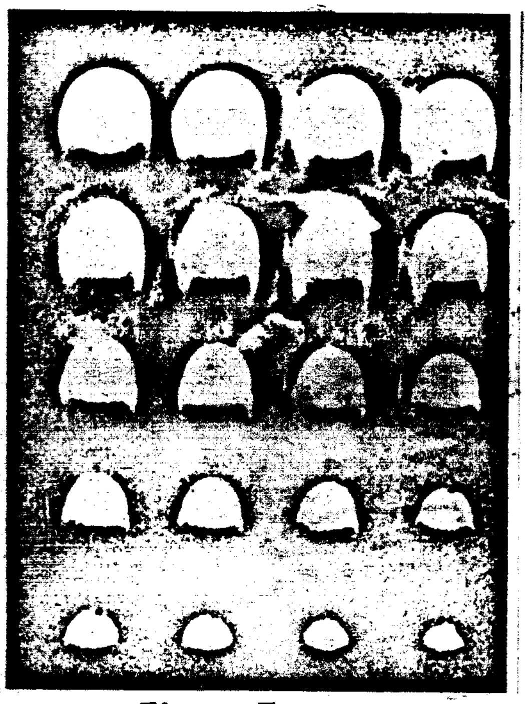

Figure 5b

Consequently, in combustion, a spherical particle will exist either in the critical region or in the subcritical region, where the boundary of the burning CO front depends on the position of the point of detachment of the boundary layer and must follow the hydrodynamic pattern, although it may be shifted slightly ahead.

If we assume that the combustion at the surface creates conditions corresponding to the subcritical region, the point of detachment of the streams should not depend on the conditions of the passing flow, and the angular distance from the frontal point should be constant.

Proceeding on the basis of this notion, we determined the angle of detachment from the experimental photographs of O. A. Tsukhanova, then calculated the velocity of the departing masses. In the physical sense, this quantity ought not to depend on the dimensions of the body or the velocity of the flow for a definite temperature interval. However, as apparent from figure 6, the velocity of the departing masses, calculated on the assumption of a constant angle of detachment, turned out to be a function of Re and is well described by a square root law (corresponding to the heavy line on the graph), since for $w = 0$ we have $c = 0$. This means there can be but one result, that under the conditions of combustion on the surface we will find ourselves in the critical region, wherein the angle of detachment depends on the conditions. Referring to the experimental investigation conducted by Fage on drag crisis effects (ref. 3), specifically an investigation of the transition from a laminar to turbulent boundary layer and detachment of the streamlines from a sphere in the critical region, the curves in this work may be used to establish the way in which the angle of detachment of the streamlines depends on the conditions in the critical zone.

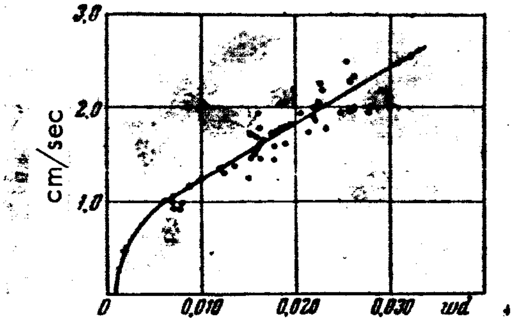

Figure 6.

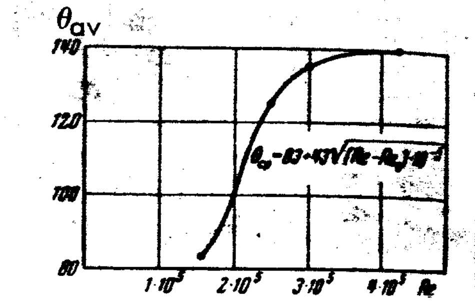

Figure 7.

As apparent from figure 7, the dependence of the angle of detachment θ of the boundary layer from a sphere on the Re number in the critical interval of the latter is well described by the formula

$$\theta = 83 + A\sqrt{Re}. \tag{7}$$

The points on the graph correspond to the experimental data of Fage, the curve corresponds to the above formula. A comparison of this material with figure 6 corroborates the conclusion that under the investigated conditions a burning particle falls in the critical region. In order to determine the numerical coefficient in front of the square root we could use O. A. Tsukhanova's experimental photographs of burning particles. The formula for calculating the angle of detachment then assumes the form /1808

$$\theta = 83 + 0{,}10\sqrt{Re}.$$

The quantity x characterizing the fraction of the surface devoted to intense combustion may be replaced by the ratio of the angle of detachment to 180° for angles near 90°, correct to 5% error, i.e., x = θ/180°.

The equation of motion of a burning spherical particle makes it possible to calculate the mean velocity of the departing masses on the basis of the experimental values of the acceleration and velocity of the particle, the

specific surface rate of combustion, the angle of detachment of the carbon monoxide flame, and the hydrodynamic drag of the particle.

An estimate of the forces acting on the particle is difficult to achieve, because, in addition to the weight force and reaction force, a flow friction force is also operative under conditions of large temperature gradients; the nonuniform temperature field near the particle must promote turbulence in the flow. The part of the flow behind the sphere will have a density and viscosity different from their freestream counterparts. The temperature field near the particle varies along the flow and is difficult to determine. Consequently, it is incorrect to calculate the drag in terms of the averaged temperature. As already stated, experiments to measure the drag of heated spherical bodies in a cold airstream in the interval of Re numbers corresponding to the experiments on the combustion of carbon particles have shown that for large temperature gradients between the sphere and flow, the drag tends to decrease. With the temperature gradients that take place in the combustion of a carbon particle, the drag coefficient will be small and near 0.1, corresponding to the drag coefficient of a sphere in the subcritical region. If we compare the magnitude of the terms in the numerator of equation (6), the first term is two or three times the second when the drag coefficient has its maximum value consistent with flow past a cold body. In combustion, the drag coefficient is considerably lower and the first term of the numerator exceeds the second term by a factor of 8 to 12. For approximate calculations, it is permissible to neglect the second term. Its inclusion will lower the value of the mean velocity of the departing masses by 10 to 12%.

The mean velocities of the departing masses were calculated on the basis of the experimental data for spherical particles of charcoal and electrode

carbon in air and an oxygen-enriched medium. The oxygen content was 29, 35, and 48%. The flow velocities past the particles were varied from 2.5 to 8 m/sec. The experiments on combustion of particles in oxygen-rich mixtures indicated /1809 a dependence of the mean velocity of the departing masses on the composition of the mixture, i.e., on the kinetics of the chemical reactions, as well as on the reactivity of the carbon (table 1).

TABLE I

Type of carbon	% O_2 in airstream	C, cm/sec	Temperature of particle (experimental), °C
Electrode carbon	20	$(4.1 \pm 0.4) \cdot 10^5$	1200
Charcoal	20	$(3.4 \pm 0.45) \cdot 10^4$	1000
The same	29	$(2.4 \pm 0.1) \cdot 10^5$	--
....	35	$(1.7 \pm 0.2) \cdot 10^5$	1200
....	48	$(1.0 \pm 0.1) \cdot 10^5$	1400

As evident from table 1, the standard error of the measurements does not exceed 13%, and the maximum deviation from the mean is within 20% limits, which is fairly satisfactory considering the coarseness of the measurements and calculations based on approximate formulas. The expected deviation from the mean should exceed 25%.

Consequently, the surface of the burning carbon particle is a source of molecular beams emanating with large velocities (on the order of 10^3 m/sec). The total effect of the emanation of these particles in different directions relative to the surface of the body then determines the nature of the motion of the burning body, as observed in the experiment. In the immediate vicinity of

the surface of the body, say of the order of one mean free path, which is very small under these conditions, the molecules execute ordered motion in the beam. After collisions with molecules of the gases flowing past the body, this ordered motion vanishes and is replaced by thermal motion.

This treatment makes it possible to apply the results obtained by Predvoditelev in 1928 for a more penetrating insight into the nature of surface-active processes. This study made use of the head-on molecular beam method to investigate the progress of the reaction in the decomposition of the crystal hydrates of salts. A torsion balance was used to determine the momentum imparted to a small vane by molecules of crystallized water emerging in vacuum. On the basis of the arguments of the kinetic theory of gases, the minimum velocity of molecules capable of overcoming the adhesion forces, hence the values of the heat of dehydration of the salts were calculated. These values were in good agreement with those determined by conventional thermochemical means. The important result here, so far as we are concerned, is the fact that twice the kinetic energy of the molecules produced by the reaction is equivalent to the thermal effect of the reaction. This means that we are in a position, given the known values of the heats of reaction, to formulate some estimate as to the relative composition of the oxides emanating from the surface of a burning body. Thus, the velocity of the departing masses was calculated from the /18 momentum acquired by the body due to its variation in mass, i.e., the mass of the carbon. Actually, however, the surface emits oxide molecules. According to the law of conservation of momentum, the momentum acquired by the burning body due to its change in mass is equal to the momentum imparted to the oxide molecules that escape from its surface.

Let us denote the fraction of ejected carbon monoxide molecules by y, the fraction of carbon dioxide molecules by z; then the law of conservation of momentum is expressed as follows:

$$12(y+z)c = 28y(1-\alpha)c_1 + 44zc_2 - 28\alpha yc_1, \tag{8}$$

where α is a coefficient defining the fraction of carbon monoxide given off in the stern part, on the assumption that CO_2 is not formed in this region.

TABLE 2

Type of carbon	% O_2 in Airstream	C_{av}, cm/sec	% CO	% CO_2	Measured temp. of particle, °C
Electrode carbon	Air	$4.1 \cdot 10^5$	43	57	1200
Charcoal	"	$3.4 \cdot 10^5$	48.5	51.5	1000
Charcoal	29	$2.4 \cdot 10^5$	56	44	--
Charcoal	35	$1.7 \cdot 10^5$	59	41	1200
Charcoal	48	$1.0 \cdot 10^5$	64	36	1400

In view of the detachment of the carbon monoxide flame, oxygen penetrates into the stern region of the spherical particles to a lesser degree than into the forward part. The oxides escaping from the stern region of the surface largely consist of CO molecules. The conditions of oxygen transport toward the frontal region of the sphere lead us to believe that, in the frontal portion, the surface ejects CO_2 molecules almost exclusively. These arguments lead to the assumption that $\alpha = 1$.

The quantities c_1 and c_2, the mean velocities of the oxide molecules, are calculated from the values of the thermal effect of the reaction in which these oxides are formed. The composition of the surface products, as calculated from equation (8), is given in table 2.

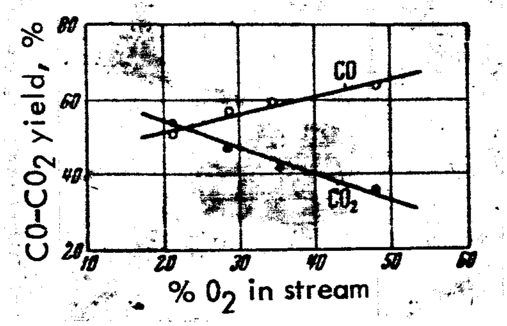

Figure 8.

These results show that in measuring the composition of the airstream, given invariant dimensions and the same limits of flow velocities past the object for which the experiments on combustion of particles in an airstream were performed, the composition of the departing products tends to increase its carbon monoxide content when the percentage oxygen in the stream is increased (fig. 8). An increase in the oxygen concentration raises the temperature of /1811 the burning particle and accelerates the process. For 1000-1200°C temperatures of the body, the ratio of the two types of carbon oxide is nearly unity, which is consistent with the results obtained by other researchers, notably L. N. Khitrin, O. A. Tsukhanova, and Kh. I. Kolodtsev, using indirect methods. This agreement indicates a correspondence between the postulated description of the active mechanism of the process. The approximations and simplifications have not affected its main characteristic features. The change in composition of the oxides when the oxygen percentage content is increased attests to a change in the chemistry of the process with increasing temperature.

On the whole, these results primarily demonstrate that the method which we have proposed herein for the investigation of combustion provides an opportunity to probe more deeply into the chemical aspect of the process on the basis of a purely physical treatment. It must be added that its application is not limited

solely to the investigation of combustion, but may be extended to the investigation of many other heterogeneous processes.

CONCLUSIONS

1. The motion of burning carbon particles in an airstream and a flowing air-oxygen mixture differs considerably from the motion of unburning bodies. The effective drag of a burning spherical particle is three or four times the drag of a cold particle of the same size, exposed to the same flow conditions.

2. The nature of the motion of the particle is governed principally by the presence of the chemical process, i.e., material exchange (mass transfer) between the body and the flow. The reactive nature of the drag effect makes it possible to establish a relationship between the kinematic characteristics of the particle motion and the variables characterizing the oxides that escape from the particle.

3. A proposed analysis based on the postulates of variable-mass mechanics enables one to ascertain the mean velocities of the masses departing from the surface of the burning carbon particle.

Experiments on the combustion of charcoal particles in oxygen-rich mixtures disclosed a variation in the mean velocity of the departing masses with a change in the chemical processes. The mean velocity of the departing masses depends on the type of carbon, i.e., on the reactivity of the latter.

4. Calculations were made to determine the possible composition of the oxides emanating from the surface of the particle. In the combustion of electrode carbon and charcoal in air, CO and CO_2 are formed in approximately equal quantities. As shown above, the quantitative ratio of the carbon monoxide and dioxide formed depends on the temperature of the particle and increases with the latter.

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